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Aaij, R.; van den Brand, J.F.J.; Dettori, F.; Ketel, T.J.; Koopman, R.; Lambert, R.W.; Raven, H.G.; Schiller, M.; Tolk, S.; LHCb, Collaboration

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Measurement of the $B_s^0 \rightarrow J/\psi K_S^0$ branching fraction[☆]

LHCb Collaboration

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ABSTRACT

The $B_s^0 \rightarrow J/\psi K_S^0$ branching fraction is measured in a data sample corresponding to 0.41 fb^{-1} of integrated luminosity collected with the LHCb detector at the LHC. This channel is sensitive to the penguin contributions affecting the $\sin 2\beta$ measurement from $B^0 \rightarrow J/\psi K_S^0$. The time-integrated branching fraction is measured to be $\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0) = (1.83 \pm 0.28) \times 10^{-5}$. This is the most precise measurement to date.

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1. Introduction

In the Standard Model (SM) CP violation arises through a single phase in the quark mixing matrix [1]. In decays of neutral B mesons to a final state which is accessible to both B and \bar{B} , the interference between the amplitude for the direct decay and the amplitude for decay via oscillation leads to a time-dependent CP -violating asymmetry between the decay time distributions of the two mesons. The mode $B^0 \rightarrow J/\psi K_S^0$ allows for the measurement of such an asymmetry, which is parametrised by the $B^0-\bar{B}^0$ mixing phase ϕ_d . In the SM this phase is equal to 2β [2], where β is one of the angles of the unitarity triangle of the mixing matrix. This phase is already measured by the B factories [3] but an improved measurement is necessary to resolve conclusively the present tension in the unitarity triangle fits [4] and determine possible small deviations from the SM value. To achieve the required precision, knowledge of the doubly Cabibbo-suppressed higher order perturbative corrections, known as *penguin diagrams*, becomes mandatory. The contributions of these penguin diagrams are difficult to calculate reliably and therefore need to be extracted directly from experimentally accessible observables. Due to $SU(3)$ flavour symmetry, these penguin diagrams can be studied in other decay modes where they are not suppressed relative to the tree level diagram. The $B_s^0 \rightarrow J/\psi K_S^0$ mode is the most promising candidate from the theoretical perspective since it is related to the $B^0 \rightarrow J/\psi K_S^0$ mode through the interchange of all d and s quarks (U -spin symmetry, a subgroup of $SU(3)$) [5] and there is a one-to-one correspondence between all decay topologies in these modes, as illustrated in Fig. 1. A further discussion regarding the theory of this decay and its potential at LHCb is given in Ref. [6].

To extract the parameters related to penguin contributions in these decays, a time-dependent CP violation study of the $B_s^0 \rightarrow J/\psi K_S^0$ mode is required. The measurement of its branching fraction is an important first step, allowing to test the U -spin symmetry assumption that lies at the basis of the proposed approach. The CDF Collaboration reported the first observation of the $B_s^0 \rightarrow J/\psi K_S^0$ decay [7]. This Letter presents a more precise measurement of this branching fraction at the LHCb experiment.

The strategy of the analysis is to measure the ratio of $B_s^0 \rightarrow J/\psi K_S^0$ and $B^0 \rightarrow J/\psi K_S^0$ event yields, which is then converted into a $B_s^0 \rightarrow J/\psi K_S^0$ branching fraction. We make use of the $B^0 \rightarrow J/\psi K^0$ branching fraction and of the ratio of B_s^0 to B^0 meson production at the LHC, denoted f_s/f_d [8].

We use an integrated luminosity of 0.41 fb^{-1} of pp collision data recorded at a centre-of-mass energy of 7 TeV during 2010 and the first half of 2011. The detector [9] is a single-arm spectrometer designed to study particles containing b or c quarks. It includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and an impact parameter resolution of 20 μm for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov (RICH) detectors. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers.

The signal simulation sample used for this analysis was generated using the PYTHIA 6.4 generator [10] configured with the parameters detailed in Ref. [11]. The EVTGEN [12], PHOTOS [13] and GEANT4 [14] packages were used to decay unstable particles,

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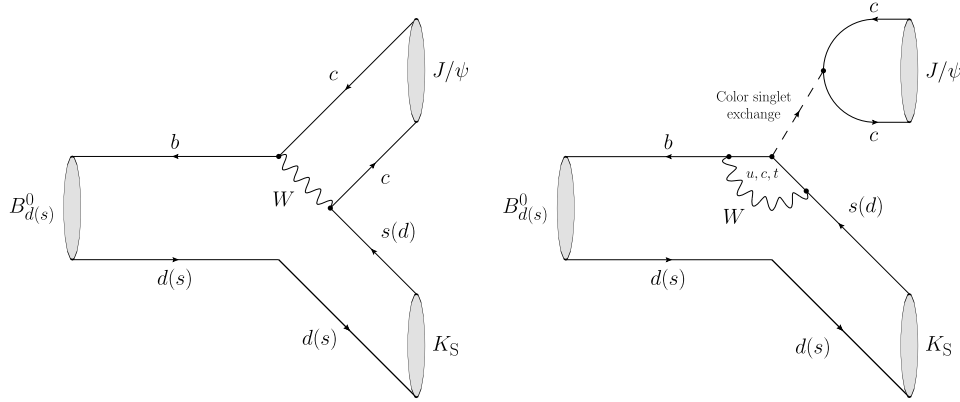


Fig. 1. Decay topologies contributing to the $B^0 \rightarrow J/\psi K_S^0$ and $B_S^0 \rightarrow J/\psi K_S^0$ channel: tree diagram to the left and penguin diagram to the right.

generate QED radiative corrections and simulate interactions in the detector, respectively.

2. Data samples and selection

We search for $B \rightarrow J/\psi K_S^0$ decays¹ where $J/\psi \rightarrow \mu^+\mu^-$ and $K_S^0 \rightarrow \pi^+\pi^-$. Events are selected by a trigger system consisting of a hardware trigger, which requires muon or hadron candidates with high transverse momentum with respect to the beam direction, p_T , followed by a two stage software trigger [15]. In the first stage a simplified event reconstruction is applied. Events are required to have either two oppositely charged muons with combined mass above $2.7 \text{ GeV}/c^2$, or at least one muon or one high- p_T track ($p_T > 1.8 \text{ GeV}/c$) with a large impact parameter with respect to any primary vertex. In the second stage a full event reconstruction is performed and only events containing $J/\psi \rightarrow \mu^+\mu^-$ candidates are retained.

In order to reduce the data to a manageable level, very loose requirements are applied to suppress background while keeping the signal efficiency high. J/ψ candidates are created from pairs of oppositely charged muons that have a common vertex and a mass in the range $3030\text{--}3150 \text{ MeV}/c^2$. The latter corresponds to about eight times the $\mu^+\mu^-$ mass resolution at the J/ψ mass and covers part of the J/ψ radiative tail. The K_S^0 selection requires two oppositely charged particles reconstructed in the tracking stations on either side of the magnet, both with hits in the vertex detector (long K_S^0 candidate) or not (downstream K_S^0 candidate). The K_S^0 candidates must be made of tracks forming a common vertex and have a mass within eight standard deviations of the K_S^0 mass and must not be compatible with the Λ mass under the mass hypothesis that one of the two tracks is a proton and the other a pion.

We select B candidates from combinations of J/ψ and K_S^0 candidates with mass $m_{J/\psi K_S^0}$ in the range $5200\text{--}5500 \text{ MeV}/c^2$. The latter is computed with the masses of the $\mu^+\mu^-$ and $\pi^+\pi^-$ pairs constrained to the J/ψ and K_S^0 masses, respectively. The mass and decay time of the B are obtained from a decay chain fit [16] that in addition constrains the B candidate to originate from the primary vertex. The χ^2 of the fit, which has eight degrees of freedom, is required to be less than 128 and the estimated uncertainty on the B mass must not exceed $30 \text{ MeV}/c^2$. B candidates are required to have a decay time larger than 0.2 ps and K_S^0 candidates to have a flight distance larger than five times its uncertainty. The offline selected signal candidate is required to be that used for the trigger decision at both software trigger stages. About 1% of the selected

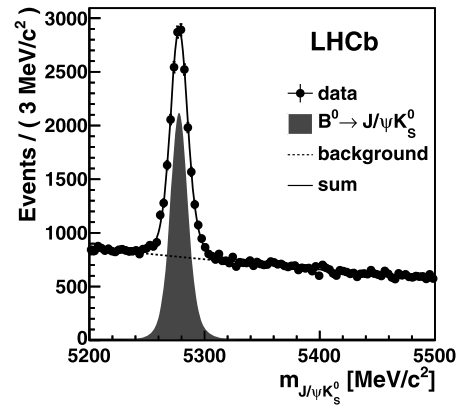


Fig. 2. Mass distribution of the $B \rightarrow J/\psi K_S^0$ candidates used to determine the PDF. The solid line is the total PDF composed of the $B^0 \rightarrow J/\psi K_S^0$ signal shown in grey and the combinatorial background represented by the dotted line.

events have several candidates sharing some final state particles. In such cases one candidate per event is selected randomly.

3. Measurement of event yields

Following the selection described above, a neural network (NN) classifier [17] is used to further discriminate between signal and background. The NN is trained entirely on data, using samples that are independent of those used to make the measurements. The training maximises the separation of signal and background events using weights determined by the *sPlot* technique [18]. We use the $B^0 \rightarrow J/\psi K_S^0$ signal in the data as a proxy for the $B_S^0 \rightarrow J/\psi K_S^0$ decay. The background events are taken from mass sidebands in the region $5390\text{--}5500 \text{ MeV}/c^2$, thus avoiding the B_S^0 signal region. A normalisation sample of one quarter of the candidates randomly selected is left out in the NN training to allow an unbiased measurement of the B^0 yield.

We perform an unbinned maximum likelihood fit to the mass distribution of the selected candidates, shown in Fig. 2, and use it to assign background and signal weights to each candidate. The probability density function (PDF) is defined as the sum of a B^0 signal component, a combinatorial background and a small contribution from partially reconstructed $B \rightarrow J/\psi K_S^0 X$ decays at masses below the B^0 mass. The mass lineshape of the $B^0 \rightarrow J/\psi K_S^0$ signal in both data and simulation exhibits non-Gaussian tails on both sides of the signal peak due to detector resolutions depending on angular distributions in the decay. We model the signal shape by an empirical model composed of two Crystal Ball

¹ B stands for B^0 or B_S^0 .

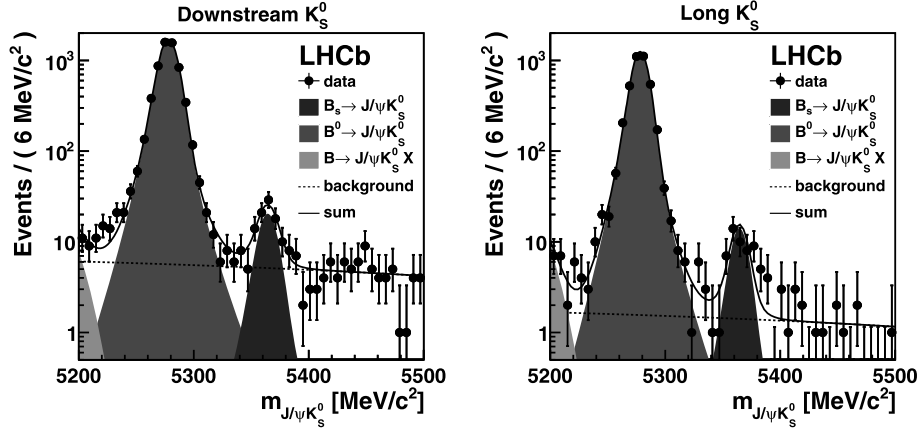


Fig. 3. Fit to full sample after the optimal NN cut has been applied with downstream K_S^0 to the left and long K_S^0 to the right.

(CB) functions [19], one of which has the tail extending to high masses. The two CB components are constrained to have the same peak and width, which are allowed to vary in the fit. The parameters describing the CB tails are taken from $B^+ \rightarrow J/\psi K^+$ events which exhibit the same behaviour as $B \rightarrow J/\psi K_S^0$. The combinatorial background is described by a second order polynomial. The $B_S^0 \rightarrow J/\psi K_S^0$ signal is not included in this fit. We extract $(14.4 \pm 0.2) \times 10^3$ B^0 events from the fit.

The NN uses information about the candidate kinematics, vertex and track quality, impact parameter, particle identification information from the RICH and muon detectors, as well as global event properties like track and primary vertex multiplicities. The variables that are used in the NN are chosen not to induce a correlation with the mass distribution. This was verified using simulated events.

To maximise the separation power, a first NN classifier using only the five most discriminating variables is used to remove 80% of the background events while keeping 95% of the B^0 signal. These variables are the χ^2 of the decay chain fit, the angle between the B momentum and the vector from the primary vertex to the decay vertex, the p_T of the K_S^0 , the estimated uncertainty on the B mass and the impact parameter χ^2 of the J/ψ .

The weighting procedure is then repeated on the remaining candidates and a second NN classifier containing 31 variables is trained. A cut is then made on the second NN output in order to optimise the expected sensitivity to the B_S^0 yield [20].

For the candidates passing the NN requirement, we determine the ratio of B_S^0 and B^0 yields for candidates containing a downstream K_S^0 or a long K_S^0 separately. The B^0 yield is measured in an unbinned likelihood fit to the normalisation sample and scaled to the full sample. The B_S^0 yield is fitted on the full sample. In both fits, the PDF is identical to that used to determine the $sWeights$ with the addition of a PDF for the B_S^0 component, which is constrained to have the same shape as the B^0 PDF, shifted by the measured B_S^0 – B^0 mass difference [21]. The results of the fits on the full samples are shown in Fig. 3 separately for candidates with downstream and long K_S^0 .

The fitted yields are listed in Table 1. The long and downstream results are compatible with each other and are combined using a weighted average.

4. Corrections and systematic uncertainties

Differences in the total selection efficiencies between the $B^0 \rightarrow J/\psi K_S^0$ and $B_S^0 \rightarrow J/\psi K_S^0$ arise because of the slight difference in momentum spectra of the B mesons and/or the final state

Table 1

B^0 and B_S^0 yields. Only statistical errors are quoted. The B^0 yield is obtained in a fit to one quarter of the events which have not been used in the NN training (normalisation sample) and then scaled to the full sample.

	Downstream K_S^0	Long K_S^0
B^0 in normalisation sample	1502 ± 39	970 ± 31
B^0 in normalisation sample (scaled to full)	6007 ± 157	3879 ± 124
B_S^0 in full sample	72 ± 11	44 ± 8
Ratio of B_S^0 to B^0	0.0120 ± 0.0018	0.0112 ± 0.0020
Ratio of B_S^0 to B^0 (weighted average, r)	0.0117 ± 0.0014	

particles. We find, using simulated events, that the geometrical acceptance of the LHCb detector is lower for the B_S^0 mode by $(1.3 \pm 0.5)\%$ where the error is due to the limited sample of simulated events. We correct for the ratio of acceptances and assign a conservative systematic uncertainty of 1.8%, which is the sum of the measured difference and its error.

The trigger, reconstruction and selection efficiencies also depend on the transverse momentum of the final state particles. Applying the trigger transverse momentum cuts on simulated B^0 and B_S^0 decays we find differences of up to 1%, which is taken as systematic uncertainty.

Due to the selection cuts and the correlation of the neural network with the decay time, a decay time acceptance function results in different selection efficiencies for the B_S^0 and the B^0 . We determine the lifetime acceptance of the whole selection chain using simulated events, and find that the ratio of the time-integrated decay time distributions for B^0 and B_S^0 is 0.975 ± 0.007 . The uncertainties on the parametrisation of the lifetime acceptance cancel almost perfectly in the ratio, while the ones related to the B^0 and B_S^0 lifetimes and the B_S^0 decay width difference $\Delta\Gamma_S$ do not.

The largest systematic uncertainty comes from the assumed mass PDF, in particular the fraction of the positive tail of the B^0 extending below the B_S^0 signal. We have studied the magnitude of this effect by leaving both tails of the CB shapes free in the fit, or by allowing the two CB shapes to have different widths. The maximal deviation we observe in the ratios of downstream or long candidates is 5%, which we take as systematic uncertainty. The effect of the uncertainty on the B_S^0 – B^0 mass difference is found to be 0.4%.

The corrections and systematic uncertainties affecting the branching fraction ratio are listed in Table 2. The total uncertainty is obtained by adding all the uncertainties in quadrature.

Table 2

Summary of corrections and systematic uncertainties on the ratio of branching fractions.

Source	Correction factor
Geometrical acceptance (ϵ_{geom})	0.987 ± 0.018
Trigger and reconstruction	1.000 ± 0.010
Decay time acceptance (ϵ_{time})	1.975 ± 0.007
Mass shape	1.000 ± 0.050
B_s^0 – B^0 mass difference	1.000 ± 0.004
Total	0.962 ± 0.053

We verify that the global event variable distributions, like the number of primary vertices and the hit multiplicities, are the same for B^0 and B_s^0 initial states using the $B_s^0 \rightarrow J/\psi\phi$ channel. We verify that the NN classifier is stable even when variables are removed from the training. We search for peaking backgrounds in simulated $b \rightarrow J/\psi X$ events, and in data by inverting the Δ veto and the K_S^0 flight distance cut. No evidence of peaking backgrounds is found. All these tests give results compatible with the measured ratio though with a larger statistical uncertainty.

5. Determination of branching fraction

Using the measured ratio $r = 0.0117 \pm 0.0014$ of $B_s^0 \rightarrow J/\psi K_S^0$ and $B^0 \rightarrow J/\psi K_S^0$ yields, the geometrical (ϵ_{geom}) and lifetime (ϵ_{time}) acceptance ratios, and assuming $f_s/f_d = 0.267_{-0.020}^{+0.021}$ [8] we measure the ratio of branching fractions

$$\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0)}{\mathcal{B}(B^0 \rightarrow J/\psi K_S^0)} = r \times \epsilon_{\text{geom}} \times \epsilon_{\text{time}} \times \frac{f_d}{f_s} = 0.0420 \pm 0.0049(\text{stat}) \pm 0.0023(\text{syst}) \pm 0.0033(f_s/f_d) \quad (1)$$

where the quoted uncertainties are statistical, systematic, and due to the uncertainty in f_s/f_d , respectively. Using the $B^0 \rightarrow J/\psi K^0$ branching fraction of $(8.71 \pm 0.32) \times 10^{-4}$ [22], we determine the time-integrated $B_s^0 \rightarrow J/\psi K_S^0$ branching fraction

$$\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0) = [1.83 \pm 0.21(\text{stat}) \pm 0.10(\text{syst}) \pm 0.14(f_s/f_d) \pm 0.07(\mathcal{B}(B^0 \rightarrow J/\psi K^0))] \times 10^{-5}$$

where the last uncertainty comes from the $B^0 \rightarrow J/\psi K^0$ branching fraction. This result is compatible with, and more precise than, the previous measurement [7].

6. Comparison with $SU(3)$ expectations

It was pointed out in Ref. [23] that because of the sizable decay width difference between the heavy and light eigenstates of the B_s^0 system, there is an ambiguity in the definition of the branching fractions of B_s^0 decays. Due to B_s^0 mixing, a branching fraction defined as the ratio of the time integrated number of B_s^0 decays to a final state and the total number of B_s^0 mesons, is not equal to the CP-average of the decay rates in the flavour eigenstate basis

$$\mathcal{B}(B_s^0 \rightarrow f)_{\text{theo}} = \frac{\tau_{B_s^0}}{2} (\Gamma(B_s^0 \rightarrow f) + \Gamma(\bar{B}_s^0 \rightarrow f)) \Big|_{t=0}, \quad (2)$$

used in the theoretical predictions; the restriction to $t = 0$ removes the effects due to the non-zero B_s decay width. To obtain the latter

quantity from the time-integrated decay rates the following correction factor

$$\frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^{J/\psi K_S^0} y_s} = 0.936 \pm 0.015, \quad (3)$$

is applied, where $y_s = \Delta\Gamma_s/2\Gamma_s$ is the normalised decay width difference between the light and heavy states and $\mathcal{A}_{\Delta\Gamma}^{J/\psi K_S^0}$ is the final-state dependent asymmetry of the B_s^0 decay rates to the $J/\psi K_S^0$ final state. In calculating this correction factor we use $y_s = 0.075 \pm 0.010$ [24] and the SM expectation $\mathcal{A}_{\Delta\Gamma}^{J/\psi K_S^0} = 0.84 \pm 0.18$ [23].

With this correction, and assuming $\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0)_{\text{theo}} = \frac{1}{2}\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^0)_{\text{theo}}$ we get the $B_s^0 \rightarrow J/\psi \bar{K}^0$ branching fraction at $t = 0$

$$\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^0)_{\text{theo}} = (3.42 \pm 0.40(\text{stat}) \pm 0.19(\text{syst}) \pm 0.27(f_s/f_d) \pm 0.13(\mathcal{B}(B^0 \rightarrow J/\psi K^0)) \pm 0.05(y_s, \mathcal{A}_{\Delta\Gamma_s})) \cdot 10^{-5}.$$

This branching fraction can be compared to theoretical expectations from $SU(3)$ symmetry, which implies an equality of the $B_s^0 \rightarrow J/\psi \bar{K}^0$ and $B^0 \rightarrow J/\psi \pi^0$ decay widths [6]

$$\mathcal{E}_{SU(3)} \equiv \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^0)_{\text{theo}}}{2\mathcal{B}(B^0 \rightarrow J/\psi \pi^0)} \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{[m_{B^0}\Phi(B^0 \rightarrow J/\psi \pi^0)]^3}{[m_{B_s^0}\Phi(B_s^0 \rightarrow J/\psi \bar{K}^0)]^3} \xrightarrow{SU(3)} 1, \quad (4)$$

where the factor two is associated with the wave function of the π^0 , $\tau_{B_{(s)}^0}$ is the mean $B_{(s)}^0$ lifetime and Φ refers to the two-body phase-space factors; see e.g. Ref. [5].

Taking the measured $\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^0)_{\text{theo}}$ and using the world average [22,21] for all other quantities, this ratio becomes

$$\mathcal{E}_{SU(3)} = 0.98 \pm 0.18$$

and is consistent with theoretical expectation of unity under $SU(3)$ symmetry.

7. Conclusion

The branching fraction of the Cabibbo-suppressed decay $B_s^0 \rightarrow J/\psi K_S^0$ is measured in a 0.41 fb^{-1} data sample collected with the LHCb detector. We determine the ratio of the $B_s^0 \rightarrow J/\psi K_S^0$ and $B^0 \rightarrow J/\psi K_S^0$ branching fractions to be $\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0)}{\mathcal{B}(B^0 \rightarrow J/\psi K_S^0)} = 0.0420 \pm 0.0049(\text{stat}) \pm 0.0023(\text{syst}) \pm 0.0033(f_s/f_d)$. Using the world-average $B^0 \rightarrow J/\psi K^0$ branching fraction we get the time-integrated branching fraction $\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0) = [1.83 \pm 0.21(\text{stat}) \pm 0.10(\text{syst}) \pm 0.14(f_s/f_d) \pm 0.07(\mathcal{B}(B^0 \rightarrow J/\psi K^0))] \times 10^{-5}$. The total uncertainty of 16% is dominated by the statistical uncertainty. This branching fraction is compatible with expectations from $SU(3)$.

With larger data samples, a time dependent CP-violation measurement of this decay will be possible, allowing the experimental determination of the penguin contributions to the $\sin 2\beta$ measurement from $B^0 \rightarrow J/\psi K_S^0$.

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LHCb Collaboration

R. Aaij³⁸, C. Abellan Beteta^{33,n}, B. Adeva³⁴, M. Adinolfi⁴³, C. Adrover⁶, A. Affolder⁴⁹, Z. Ajaltouni⁵, J. Albrecht³⁵, F. Alessio³⁵, M. Alexander⁴⁸, S. Ali³⁸, G. Alkhazov²⁷, P. Alvarez Cartelle³⁴, A.A. Alves Jr.²², S. Amato², Y. Amhis³⁶, J. Anderson³⁷, R.B. Appleby⁵¹, O. Aquines Gutierrez¹⁰, F. Archilli^{18,35}, L. Arrabito^{55,q}, A. Artamonov³², M. Artuso^{53,35}, E. Aslanides⁶, G. Auriemma^{22,m}, S. Bachmann¹¹, J.J. Back⁴⁵, V. Balagura^{28,35}, W. Baldini¹⁶, R.J. Barlow⁵¹, C. Barschel³⁵, S. Barsuk⁷, W. Barter⁴⁴, A. Bates⁴⁸, C. Bauer¹⁰, Th. Bauer³⁸, A. Bay³⁶, I. Bediaga¹, S. Belogurov²⁸, K. Belous³², I. Belyaev²⁸, E. Ben-Haim⁸, M. Benayoun⁸, G. Bencivenni¹⁸, S. Benson⁴⁷, J. Benton⁴³, R. Bernet³⁷, M.-O. Bettler¹⁷, M. van Beuzekom³⁸, A. Bien¹¹, S. Bifani¹², T. Bird⁵¹, A. Bizzeti^{17,h}, P.M. Bjørnstad⁵¹, T. Blake³⁵, F. Blanc³⁶, C. Blanks⁵⁰, J. Blouw¹¹, S. Blusk⁵³, A. Bobrov³¹, V. Bocci²², A. Bondar³¹, N. Bondar²⁷, W. Bonivento¹⁵, S. Borghi^{48,51}, A. Borgia⁵³, T.J.V. Bowcock⁴⁹, C. Bozzi¹⁶, T. Brambach⁹, J. van den Brand³⁹, J. Bressieux³⁶, D. Brett⁵¹, M. Britsch¹⁰, T. Britton⁵³, N.H. Brook⁴³, H. Brown⁴⁹, A. Büchler-Germann³⁷, I. Burducea²⁶, A. Bursche³⁷, J. Buytaert³⁵, S. Cadeddu¹⁵, O. Callot⁷, M. Calvi^{20,j}, M. Calvo Gomez^{33,n}, A. Camboni³³, P. Campana^{18,35}, A. Carbone¹⁴, G. Carboni^{21,k}, R. Cardinale^{19,35,i}, A. Cardini¹⁵, L. Carson⁵⁰, K. Carvalho Akiba², G. Casse⁴⁹, M. Cattaneo³⁵, Ch. Cauet⁹, M. Charles⁵², Ph. Charpentier³⁵, N. Chiapolini³⁷, K. Ciba³⁵, X. Cid Vidal³⁴, G. Ciezarek⁵⁰, P.E.L. Clarke⁴⁷, M. Clemencic³⁵, H.V. Cliff⁴⁴, J. Closier³⁵, C. Coca²⁶, V. Coco³⁸, J. Cogan⁶, P. Collins³⁵, A. Comerma-Montells³³, A. Contu⁵², A. Cook⁴³, M. Coombes⁴³, G. Corti³⁵, B. Couturier³⁵, G.A. Cowan³⁶, R. Currie⁴⁷, C. D'Ambrosio³⁵, P. David⁸, P.N.Y. David³⁸, I. De Bonis⁴, K. De Bruyn³⁸, S. De Capua^{21,k}, M. De Cian³⁷, F. De Lorenzi¹², J.M. De Miranda¹, L. De Paula², P. De Simone¹⁸, D. Decamp⁴, M. Deckenhoff⁹, H. Degaudenzi^{36,35}, L. Del Buono⁸, C. Deplano¹⁵, D. Derkach^{14,35}, O. Deschamps⁵, F. Dettori³⁹, J. Dickens⁴⁴, H. Dijkstra³⁵, P. Diniz Batista¹, F. Domingo Bonal^{33,n}, S. Donleavy⁴⁹, F. Dordei¹¹, A. Dosil Suárez³⁴, D. Dossett⁴⁵, A. Dovbnya⁴⁰, F. Dupertuis³⁶, R. Dzhelezhyan³², A. Dziurda²³, S. Easo⁴⁶, U. Egede⁵⁰, V. Egorychev²⁸, S. Eidelman³¹, D. van Eijk³⁸, F. Eisele¹¹, S. Eisenhardt⁴⁷, R. Ekelhof⁹, L. Eklund⁴⁸, Ch. Elsasser³⁷, D. Elsby⁴², D. Esperante Pereira³⁴,

A. Falabella^{16,14,e}, C. Färber¹¹, G. Fardell⁴⁷, C. Farinelli³⁸, S. Farry¹², V. Fave³⁶, V. Fernandez Albor³⁴, M. Ferro-Luzzi³⁵, S. Filippov³⁰, C. Fitzpatrick⁴⁷, M. Fontana¹⁰, F. Fontanelli^{19,i}, R. Forty³⁵, O. Francisco², M. Frank³⁵, C. Frei³⁵, M. Frosini^{17,f}, S. Furcas²⁰, A. Gallas Torreira³⁴, D. Galli^{14,c}, M. Gandelman², P. Gandini⁵², Y. Gao³, J.-C. Garnier³⁵, J. Garofoli⁵³, J. Garra Tico⁴⁴, L. Garrido³³, D. Gascon³³, C. Gaspar³⁵, R. Gauld⁵², N. Gauvin³⁶, M. Gersabeck³⁵, T. Gershon^{45,35}, Ph. Ghez⁴, V. Gibson⁴⁴, V.V. Gligorov³⁵, C. Göbel^{54,p}, D. Golubkov²⁸, A. Golutvin^{50,28,35}, A. Gomes², H. Gordon⁵², M. Grabalosa Gándara³³, R. Graciani Diaz³³, L.A. Granado Cardoso³⁵, E. Graugés³³, G. Graziani¹⁷, A. Grecu²⁶, E. Greening⁵², S. Gregson⁴⁴, B. Gui⁵³, E. Gushchin³⁰, Yu. Guz³², T. Gys³⁵, C. Hadjivasiliou⁵³, G. Haefeli³⁶, C. Haen³⁵, S.C. Haines⁴⁴, T. Hampson⁴³, S. Hansmann-Menzemer¹¹, R. Harji⁵⁰, N. Harnew⁵², J. Harrison⁵¹, P.F. Harrison⁴⁵, T. Hartmann^{56,r}, J. He⁷, V. Heijne³⁸, K. Hennessy⁴⁹, P. Henrard⁵, J.A. Hernando Morata³⁴, E. van Herwijnen³⁵, E. Hicks⁴⁹, K. Holubyev¹¹, P. Hopchev⁴, W. Hulsbergen³⁸, P. Hunt⁵², T. Huse⁴⁹, R.S. Huston¹², D. Hutchcroft⁴⁹, D. Hynds⁴⁸, V. Iakovenko⁴¹, P. Ilten¹², J. Imong⁴³, R. Jacobsson³⁵, A. Jaeger¹¹, M. Jahjah Hussein⁵, E. Jans³⁸, F. Jansen³⁸, P. Jatton³⁶, B. Jean-Marie⁷, F. Jing³, M. John⁵², D. Johnson⁵², C.R. Jones⁴⁴, B. Jost³⁵, M. Kabbalo⁹, S. Kandybei⁴⁰, M. Karacson³⁵, T.M. Karbach⁹, J. Keaveney¹², I.R. Kenyon⁴², U. Kerzel³⁵, T. Ketel³⁹, A. Keune³⁶, B. Khanji⁶, Y.M. Kim⁴⁷, M. Knecht³⁶, R.F. Koopman³⁹, P. Koppenburg^{38,*}, M. Korolev²⁹, A. Kozlinskiy³⁸, L. Kravchuk³⁰, K. Kreplin¹¹, M. Kreps⁴⁵, G. Krocker¹¹, P. Krokovny³¹, F. Kruse⁹, K. Kruzelecki³⁵, M. Kucharczyk^{20,23,35,j}, V. Kudryavtsev³¹, T. Kvaratskheliya^{28,35}, V.N. La Thi³⁶, D. Lacarrere³⁵, G. Lafferty⁵¹, A. Lai¹⁵, D. Lambert⁴⁷, R.W. Lambert³⁹, E. Lanciotti³⁵, G. Lanfranchi¹⁸, C. Langenbruch¹¹, T. Latham⁴⁵, C. Lazzeroni⁴², R. Le Gac⁶, J. van Leerdam³⁸, J.-P. Lees⁴, R. Lefèvre⁵, A. Leflat^{29,35}, J. Lefrançois⁷, O. Leroy⁶, T. Lesiak²³, L. Li³, L. Li Gioi⁵, M. Lieng⁹, M. Liles⁴⁹, R. Lindner³⁵, C. Linn¹¹, B. Liu³, G. Liu³⁵, J. von Loeben²⁰, J.H. Lopes², E. Lopez Asamar³³, N. Lopez-March³⁶, H. Lu³, J. Luisier³⁶, A. Mac Raighne⁴⁸, F. Machefert⁷, I.V. Machikhiliyan^{4,28}, F. Maciuc¹⁰, O. Maev^{27,35}, J. Magnin¹, S. Malde⁵², R.M.D. Mamunur³⁵, G. Manca^{15,d}, G. Mancinelli⁶, N. Mangiafave⁴⁴, U. Marconi¹⁴, R. Märki³⁶, J. Marks¹¹, G. Martellotti²², A. Martens⁸, L. Martin⁵², A. Martín Sánchez⁷, M. Martinelli³⁸, D. Martinez Santos³⁵, A. Massafferri¹, Z. Mathe¹², C. Matteuzzi²⁰, M. Matveev²⁷, E. Maurice⁶, B. Maynard⁵³, A. Mazurov^{16,30,35}, G. McGregor⁵¹, R. McNulty¹², M. Meissner¹¹, M. Merk³⁸, J. Merkel⁹, S. Miglioranza³⁵, D.A. Milanese¹³, M.-N. Minard⁴, J. Molina Rodriguez⁵⁴, S. Monteil⁵, D. Moran¹², P. Morawski²³, R. Mountain⁵³, I. Mous³⁸, F. Muheim⁴⁷, K. Müller³⁷, R. Muresan²⁶, B. Muryn²⁴, B. Muster³⁶, J. Mylroie-Smith⁴⁹, P. Naik⁴³, T. Nakada³⁶, R. Nandakumar⁴⁶, I. Nasteva¹, M. Needham⁴⁷, N. Neufeld³⁵, A.D. Nguyen³⁶, C. Nguyen-Mau^{36,o}, M. Nicol⁷, V. Niess⁵, N. Nikitin²⁹, T. Nikodem¹¹, A. Nomerotski^{52,35}, A. Novoselov³², A. Oblakowska-Mucha²⁴, V. Obraztsov³², S. Oggero³⁸, S. Ogilvy⁴⁸, O. Okhrimenko⁴¹, R. Oldeman^{15,35,d}, M. Orlandea²⁶, J.M. Otalora Goicochea², P. Owen⁵⁰, B.K. Pal⁵³, J. Palacios³⁷, A. Palano^{13,b}, M. Palutan¹⁸, J. Panman³⁵, A. Papanestis⁴⁶, M. Pappagallo⁴⁸, C. Parkes⁵¹, C.J. Parkinson⁵⁰, G. Passaleva¹⁷, G.D. Patel⁴⁹, M. Patel⁵⁰, S.K. Paterson⁵⁰, G.N. Patrick⁴⁶, C. Patrignani^{19,i}, C. Pavel-Nicorescu²⁶, A. Pazos Alvarez³⁴, A. Pellegrino³⁸, G. Penso^{22,l}, M. Pepe Altarelli³⁵, S. Perazzini^{14,c}, D.L. Perego^{20,j}, E. Perez Trigo³⁴, A. Pérez-Calero Yzquierdo³³, P. Perret⁵, M. Perrin-Terrin⁶, G. Pessina²⁰, A. Petrolini^{19,i}, A. Phan⁵³, E. Picatoste Olloqui³³, B. Pie Valls³³, B. Pietrzyk⁴, T. Pilař⁴⁵, D. Pinci²², R. Plackett⁴⁸, S. Playfer⁴⁷, M. Plo Casasus³⁴, G. Polok²³, A. Poluektov^{45,31}, E. Polycarpo², D. Popov¹⁰, B. Popovici²⁶, C. Potterat³³, A. Powell⁵², J. Prisciandaro³⁶, V. Pugatch⁴¹, A. Puig Navarro³³, W. Qian⁵³, J.H. Rademacker⁴³, B. Rakotomiamanana³⁶, M.S. Rangel², I. Raniuk⁴⁰, G. Raven³⁹, S. Redford⁵², M.M. Reid⁴⁵, A.C. dos Reis¹, S. Ricciardi⁴⁶, A. Richards⁵⁰, K. Rinnert⁴⁹, D.A. Roa Romero⁵, P. Robbe⁷, E. Rodrigues^{48,51}, F. Rodrigues², P. Rodriguez Perez³⁴, G.J. Rogers⁴⁴, S. Roiser³⁵, V. Romanovsky³², M. Rosello^{33,n}, J. Rouvinet³⁶, T. Ruf³⁵, H. Ruiz³³, G. Sabatino^{21,k}, J.J. Saborido Silva³⁴, N. Sagidova²⁷, P. Sail⁴⁸, B. Saitta^{15,d}, C. Salzmann³⁷, M. Sannino^{19,i}, R. Santacesaria²², C. Santamarina Rios³⁴, R. Santinelli³⁵, E. Santovetti^{21,k}, M. Sapunov⁶, A. Sarti^{18,l}, C. Satriano^{22,m}, A. Satta²¹, M. Savrie^{16,e}, D. Savrina²⁸, P. Schaack⁵⁰, M. Schiller³⁹, S. Schleich⁹, M. Schlupp⁹, M. Schmelling¹⁰, B. Schmidt³⁵, O. Schneider³⁶, A. Schopper³⁵, M.-H. Schune⁷, R. Schwemmer³⁵, B. Sciascia¹⁸, A. Sciubba^{18,l}, M. Seco³⁴, A. Semennikov²⁸, K. Senderowska²⁴, I. Sepp⁵⁰, N. Serra³⁷, J. Serrano⁶, P. Seyfert¹¹, M. Shapkin³², I. Shapoval^{40,35}, P. Shatalov²⁸, Y. Shcheglov²⁷, T. Shears⁴⁹, L. Shekhtman³¹, O. Shevchenko⁴⁰, V. Shevchenko²⁸, A. Shires⁵⁰, R. Silva Coutinho⁴⁵, T. Skwarnicki⁵³, N.A. Smith⁴⁹,

E. Smith^{52,46}, K. Sobczak⁵, F.J.P. Soler⁴⁸, A. Solomin⁴³, F. Soomro^{18,35}, B. Souza De Paula², B. Spaan⁹, A. Sparkes⁴⁷, P. Spradlin⁴⁸, F. Stagni³⁵, S. Stahl¹¹, O. Steinkamp³⁷, S. Stoica²⁶, S. Stone^{53,35}, B. Storaci³⁸, M. Straticiuc²⁶, U. Straumann³⁷, V.K. Subbiah³⁵, S. Swientek⁹, M. Szczekowski²⁵, P. Szczypka³⁶, T. Szumlak²⁴, S. T'Jampens⁴, E. Teodorescu²⁶, F. Teubert³⁵, C. Thomas⁵², E. Thomas³⁵, J. van Tilburg¹¹, V. Tisserand⁴, M. Tobin³⁷, S. Tolk³⁹, S. Topp-Joergensen⁵², N. Torr⁵², E. Tournefier^{4,50}, S. Tourneur³⁶, M.T. Tran³⁶, A. Tsaregorodtsev⁶, N. Tuning³⁸, M. Ubeda Garcia³⁵, A. Ukleja²⁵, P. Urquijo⁵³, U. Uwer¹¹, V. Vagnoni¹⁴, G. Valenti¹⁴, R. Vazquez Gomez³³, P. Vazquez Regueiro³⁴, S. Vecchi¹⁶, J.J. Velthuis⁴³, M. Veltri^{17,g}, B. Viaud⁷, I. Videau⁷, D. Vieira², X. Vilasis-Cardona^{33,n}, J. Visniakov³⁴, A. Vollhardt³⁷, D. Volyanskyy¹⁰, D. Voong⁴³, A. Vorobyev²⁷, V. Vorobyev³¹, H. Voss¹⁰, R. Waldi⁵⁶, S. Wandernoth¹¹, J. Wang⁵³, D.R. Ward⁴⁴, N.K. Watson⁴², A.D. Webber⁵¹, D. Websdale⁵⁰, M. Whitehead⁴⁵, D. Wiedner¹¹, L. Wiggers³⁸, G. Wilkinson⁵², M.P. Williams^{45,46}, M. Williams⁵⁰, F.F. Wilson⁴⁶, J. Wishahi⁹, M. Witek²³, W. Witzeling³⁵, S.A. Wotton⁴⁴, K. Wyllie³⁵, Y. Xie⁴⁷, F. Xing⁵², Z. Xing⁵³, Z. Yang³, R. Young⁴⁷, O. Yushchenko³², M. Zangoli¹⁴, M. Zavertyaev^{10,a}, F. Zhang³, L. Zhang⁵³, W.C. Zhang¹², Y. Zhang³, A. Zhelezov¹¹, L. Zhong³, A. Zvyagin³⁵

¹ Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

² Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

³ Center for High Energy Physics, Tsinghua University, Beijing, China

⁴ LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France

⁵ Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France

⁶ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

⁷ LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

⁸ LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France

⁹ Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

¹⁰ Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

¹¹ Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

¹² School of Physics, University College Dublin, Dublin, Ireland

¹³ Sezione INFN di Bari, Bari, Italy

¹⁴ Sezione INFN di Bologna, Bologna, Italy

¹⁵ Sezione INFN di Cagliari, Cagliari, Italy

¹⁶ Sezione INFN di Ferrara, Ferrara, Italy

¹⁷ Sezione INFN di Firenze, Firenze, Italy

¹⁸ Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy

¹⁹ Sezione INFN di Genova, Genova, Italy

²⁰ Sezione INFN di Milano Bicocca, Milano, Italy

²¹ Sezione INFN di Roma Tor Vergata, Roma, Italy

²² Sezione INFN di Roma La Sapienza, Roma, Italy

²³ Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

²⁴ AGH University of Science and Technology, Kraków, Poland

²⁵ Soltan Institute for Nuclear Studies, Warsaw, Poland

²⁶ Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania

²⁷ Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia

²⁸ Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia

²⁹ Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia

³⁰ Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia

³¹ Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia

³² Institute for High Energy Physics (IHEP), Protvino, Russia

³³ Universitat de Barcelona, Barcelona, Spain

³⁴ Universidad de Santiago de Compostela, Santiago de Compostela, Spain

³⁵ European Organization for Nuclear Research (CERN), Geneva, Switzerland

³⁶ Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

³⁷ Physik-Institut, Universität Zürich, Zürich, Switzerland

³⁸ Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands

³⁹ Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands

⁴⁰ NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine

⁴¹ Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine

⁴² University of Birmingham, Birmingham, United Kingdom

⁴³ H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom

⁴⁴ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

⁴⁵ Department of Physics, University of Warwick, Coventry, United Kingdom

⁴⁶ STFC Rutherford Appleton Laboratory, Didcot, United Kingdom

⁴⁷ School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁴⁸ School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

⁴⁹ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

⁵⁰ Imperial College London, London, United Kingdom

⁵¹ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

⁵² Department of Physics, University of Oxford, Oxford, United Kingdom

⁵³ Syracuse University, Syracuse, NY, United States

⁵⁴ Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil

⁵⁵ CC-IN2P3, CNRS/IN2P3, Lyon-Villeurbanne, France

⁵⁶ Institut für Physik, Universität Rostock, Rostock, Germany

* Corresponding author.

E-mail address: patrick.koppenburg@cern.ch (P. Koppenburg).

^a P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.

^b Università di Bari, Bari, Italy.

^c Università di Bologna, Bologna, Italy.

^d Università di Cagliari, Cagliari, Italy.

^e Università di Ferrara, Ferrara, Italy.

^f Università di Firenze, Firenze, Italy.

^g Università di Urbino, Urbino, Italy.

^h Università di Modena e Reggio Emilia, Modena, Italy.

ⁱ Università di Genova, Genova, Italy.

^j Università di Milano Bicocca, Milano, Italy.

^k Università di Roma Tor Vergata, Roma, Italy.

^l Università di Roma La Sapienza, Roma, Italy.

^m Università della Basilicata, Potenza, Italy.

ⁿ LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

^o Hanoi University of Science, Hanoi, Viet Nam.

^p Associated to Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil.

^q Associated to CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

^r Associated to Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany.